Experimental Identification of Time-Delay of Human Balancing Using Cepstrum

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Abstract

In spite of the increasing efforts related to human balancing tasks, neural processes behind balancing mechanism are still not fully understood. The models that fit best to the different experimental results involve many uncertain factors. Consequently a wide range of various controller concepts and their modifications appear in the literature as possible candidates for human balancing, e.g. [1, 2, 3].

We suppose that a linear controller is appropriate for modeling the human balancing during balance board trials (see Fig. 1). As a fundamental example, balancing on a pinned balance board is also studied in [1], however the authors consider nonlinear terms in the feedback control. The human sensory system and vision provides information for the brain about the pose of the body, the angular velocity and acceleration of the head [2]. Thus, our model contains proportional, derivative and optionally acceleration feedback (PD and PDA respectively). These feedback terms are supposed to involve time delay in the closed-loop system [2, 3], for which the equation of motion assumes the form:

$$\mathbf{M}(\mathbf{q}(t))\ddot{\mathbf{q}}(t)+\mathbf{C}(\mathbf{q}(t),\dot{\mathbf{q}}(t))=-\mathbf{P}\mathbf{q}(t-\tau_{\mathrm{P}})-\mathbf{D}\dot{\mathbf{q}}(t-\tau_{\mathrm{D}})-\mathbf{A}\ddot{\mathbf{q}}(t-\tau_{\mathrm{A}})\,, \tag{1}$$

where gain matrices **P**, **D** and **A** contains 18 gain parameters in our model: proportional, derivative and acceleration feedback parameters for each of angles ϑ, φ_{u} and φ_{l} with respect to torques T_{a} and T_{h} exerted at the ankles and the hip, respectively. The controller model allows different values of time delays for each feedback term. The identification of these time delays is a challenging task, and many papers focus on it, e.g. [4].

If time delay and acceleration feedback is present at the same time, then the mathematical model of the controlled system is a neutral delay-differential equation (NDDE), because the term of highest derivative appears with a delayed argument. Neutral mechanical systems have the property that the discontinuities of the acceleration directly appear in the delayed terms, thus instead of smoothen slowly, the discontinuities accumulate [1, 3].

Our idea is to use the spectrum and cepstrum of the solution of NDDEs for the identification of time delay. In NDDEs the discontinuities and peaks do not smoothen therefore they are periodically repeated with a period equal to the time delay. A peak, which corresponds to the frequency of these periodic-like components of the signal, appears in the spectrum. Since the periodic signal is not sinusoidal, the peak in the spectrum involves higher harmonics too. These periodically repeated peaks in the spectrum (non-sinusoidal periodic function of frequency) generate peaks in the cepstrum (the spectrum of the spectrum) as well. All in all, we can say that the spectrum of a periodic signal usually contains finite number of peaks, but as a consequence of the time-delayed acceleration feedback, a peak appears in every equal interval of the domain of the spectrum and the cepstrum. Since the cepstrum is in time domain, this interval is equal to the delay of the system.

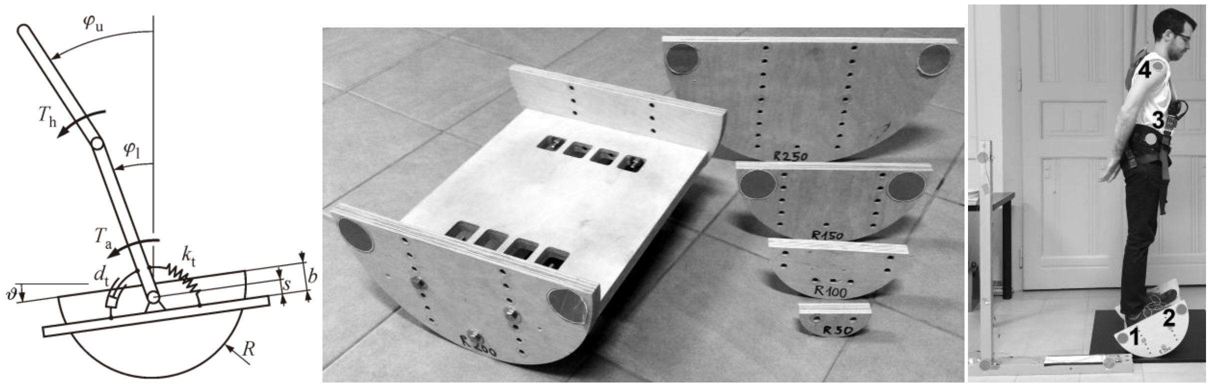

Figure 1. *left:* mechanical model of a balancing person on balance board; *middle:* balance board with interchangeable arcs; *right:* balancing person equipped with passive markers 1-4 for motion capturing

The idea was tested on a simulation result of a NDDE, for which the non-linear equation of motion of an inverted pendulum with PDA control was applied:

$$\ddot{\varphi}(t)-\frac{3}{2}\frac{g}{l}\sin(\varphi(t))=-P\varphi(t-\tau)-D\varphi(t-\tau)-A\varphi(t-\tau)\,. \qquad (2)$$

The spectrum and cepstrum of the numerical solution are shown in Fig 2 left. The peaks in the cepstrum indicate the pre-defined $\tau=0.2\mathrm{s}$ time delay.

Laboratory experiments were carried out for 7 subjects balancing on a balance board with different radii (Fig 1 middle and right). The tilt angle ϑ of the balance board, the position of the hip and the shoulder was logged in the sagittal plane. A high resolution camera was used with 50Hz sampling frequency. The angles φ_{u} and φ_{l} of the lower and upper pendulum were calculated based on the measured marker positions.

If a subject was able to balance for 60 second without falling, then the trial was considered to be stable. For each subject 9 different R and h parameter sets were considered. In this work the spectrum and cepstrum analysis were carried out for the stable cases only.

The spectrum and cepstrum of the measured signals for ϑ, φ_{u} and φ_{l} were analyzed. An example case is shown in Fig 2 middle and right panels respectively. The number of peaks of the cepstrum was determined for the quefrency range between 0s and 1s. In this first trial of our concept, equal time-delays were assumed for the different terms: $\tau=\tau_{\mathrm{P}}=\tau_{\mathrm{D}}=\tau_{\mathrm{A}}$. Assuming a uniform distance between the peaks, the average time delay was determined. The average value of the time-delay was about $\tau=85\mathrm{ms}$.

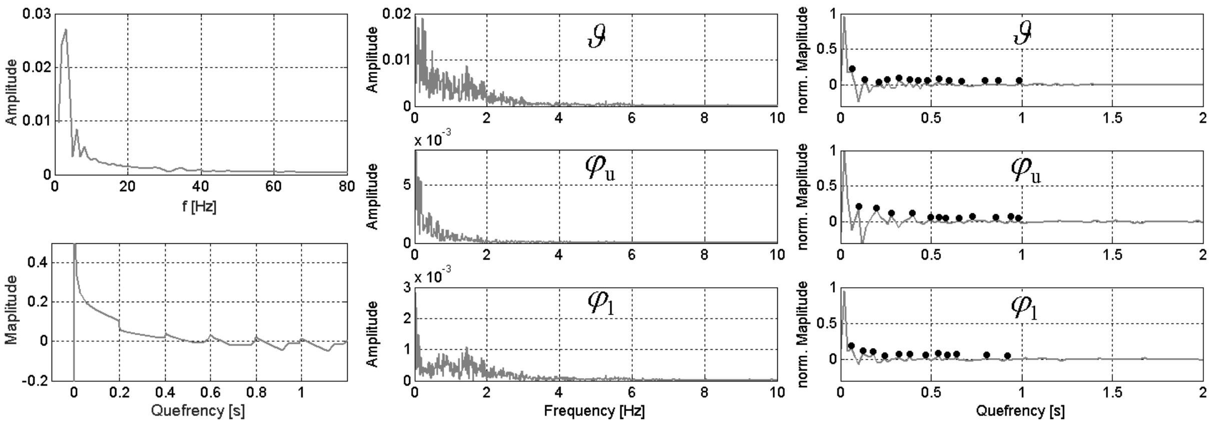

Figure 2. *left:* spectrum and cepstrum of a simulated signal; *middle and right:* spectrum and cepstrum of measured signals

Although, our results show the feasibility of the concept of determining the time-delay using cepstrum, a few issues have to be clarified in further research work. Human sense organs have dead zone, like artificial sensors [5]. The presence of dead zones causes nonlinearity, which affects the spectrum and the cepstrum. Multiple delays can cause intricate situation, and their separate identification may induce crucial problems.

The expected periodic-like pattern of the peaks appeared in the cepstrum, so the results do not exclude the validity of the linear compensator model and the possibility of the presence of the delayed acceleration feedback term.

References

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